Development of a multi-ring ν_e sample at the T2K far detector

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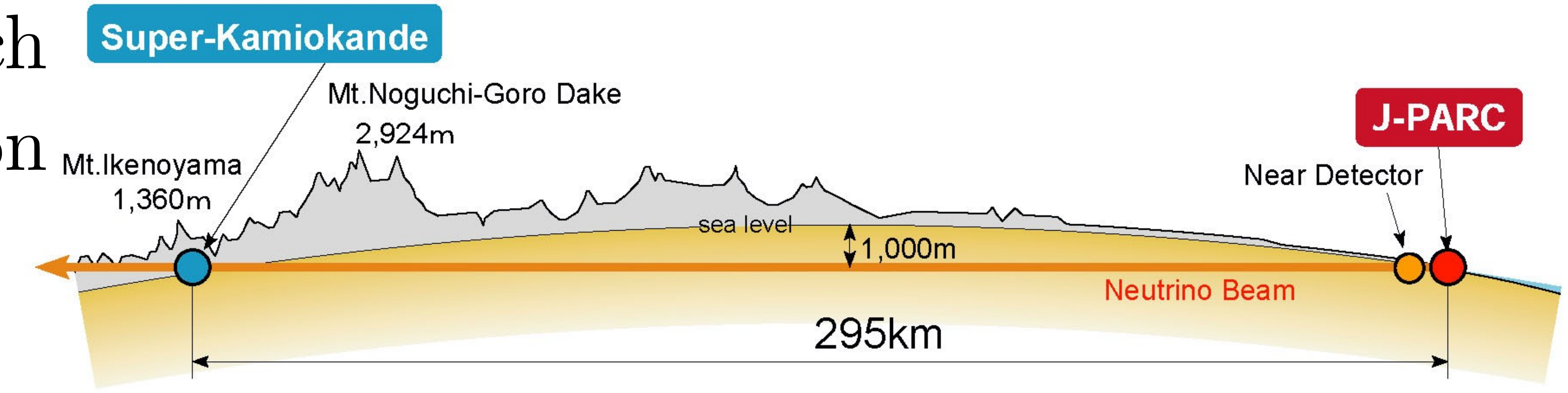
The Tokai-to-Kamioka (T2K) Experiment

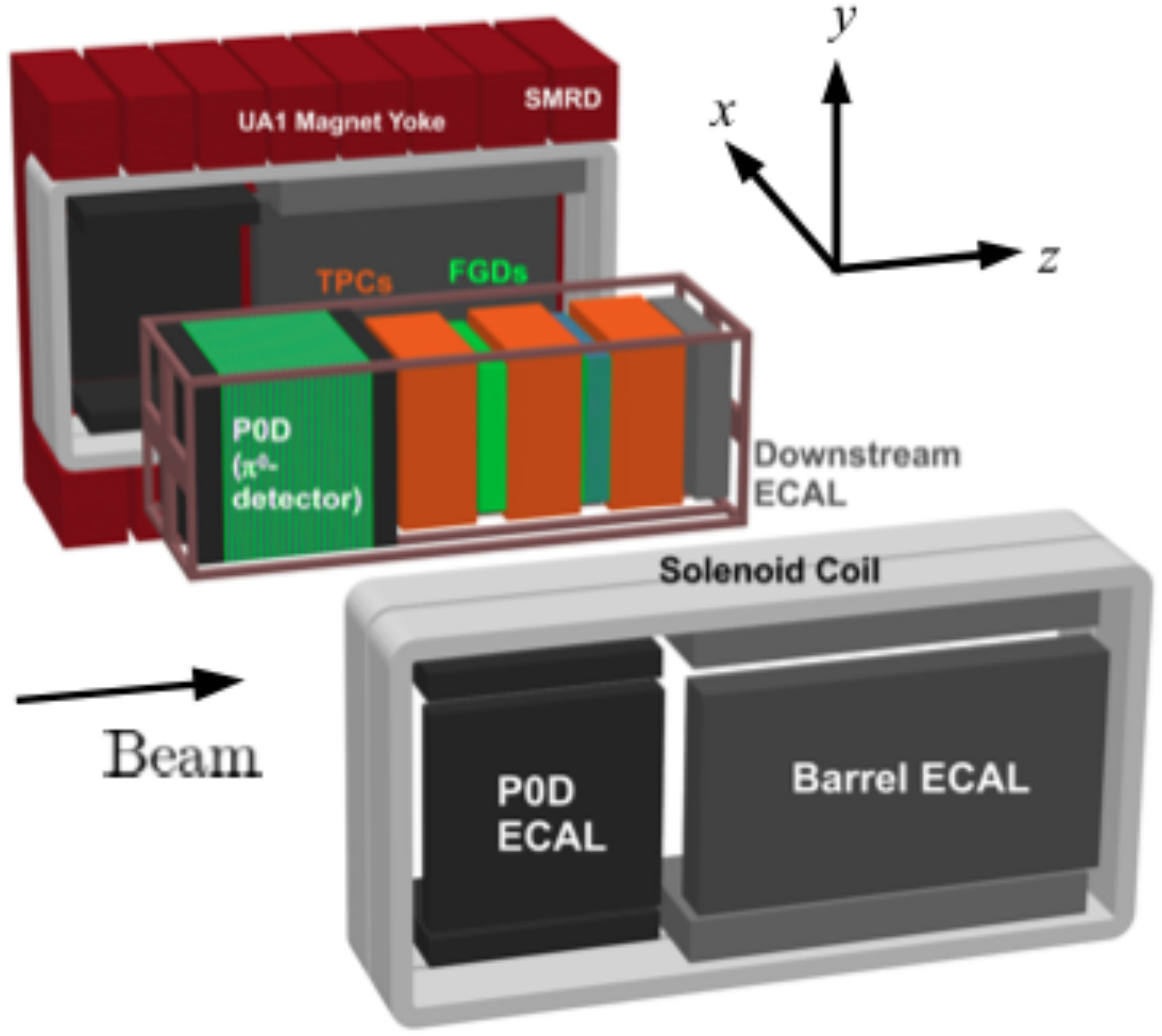
- T2K is an accelerator-based long-baseline (295 km) neutrino experiment which observes ν_e appearance and ν_μ disappearance from a ν_μ beam generated at J-PARC accelerator facility in Tokai, Japan.
- The beam energy is peaked at 0.6 GeV and the neutrino events are observed using a near detector (ND280) located 280m downstream and a far detector (Super Kamiokande) which is 295 km away from the beam production target.



The Tokai-to-Kamioka (T2K) Experiment

The near detector system consists of:

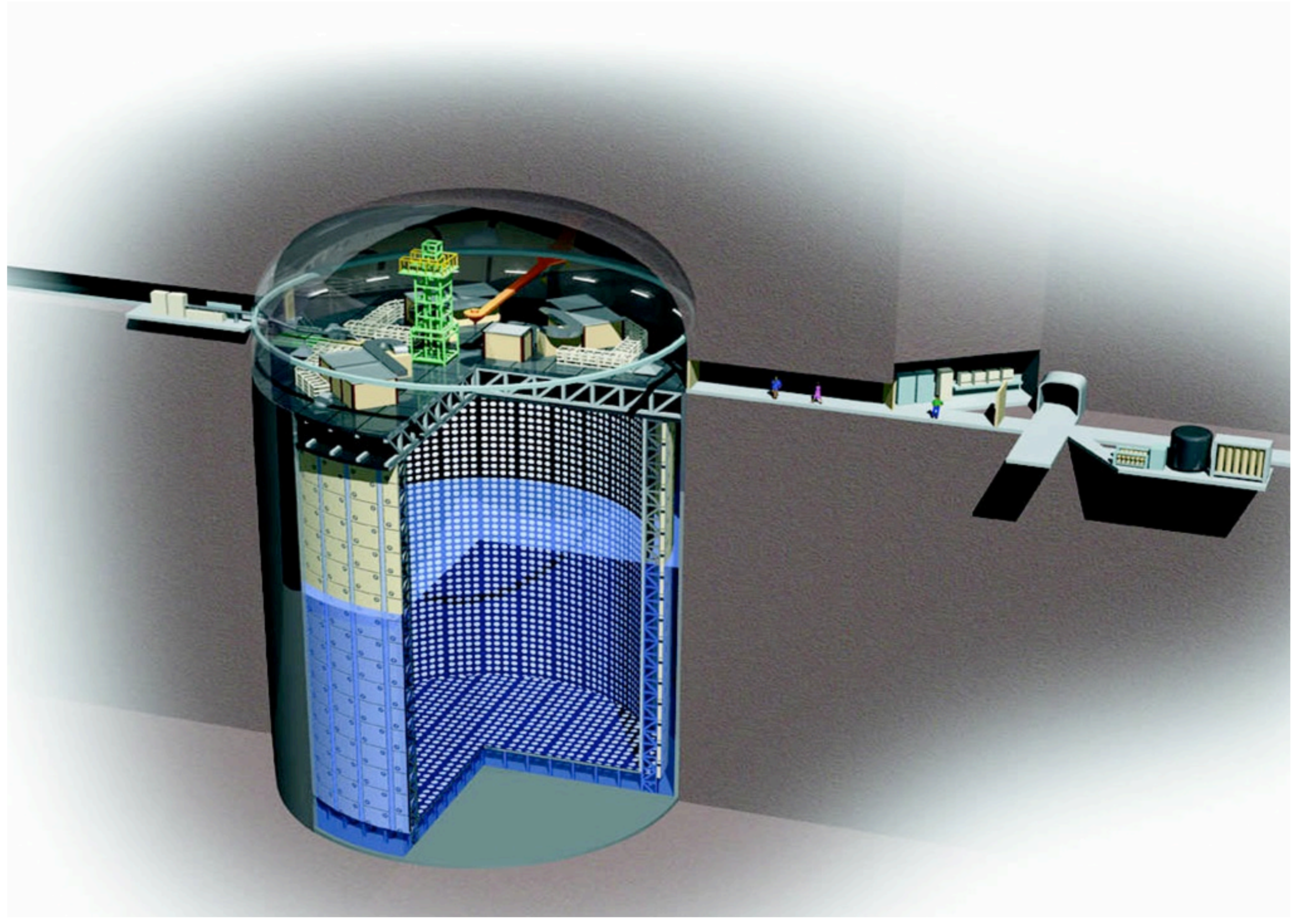
- INGRID, which measures the beam intensity and direction through interaction with iron.
- ND280, which measures the neutrino flux before any oscillations can occur.



T2K's far detector,

- Super Kamiokande (SK) is a 50kton water Cherenkov detector that observes Cherenkov rings caused by charged particles produced in neutrino interactions with water.

✦ ND280 and SK are oriented 2.5° off-axis with respect to the neutrino beam, giving the detectors access to neutrinos with a narrower band of energies compared to the on-axis neutrinos.



Physics goals of T2K

- Observation of ν_e coming from $\nu_\mu \to \nu_e$ oscillations. This confirms that the third mixing angle, $\theta_{13} > 0$.

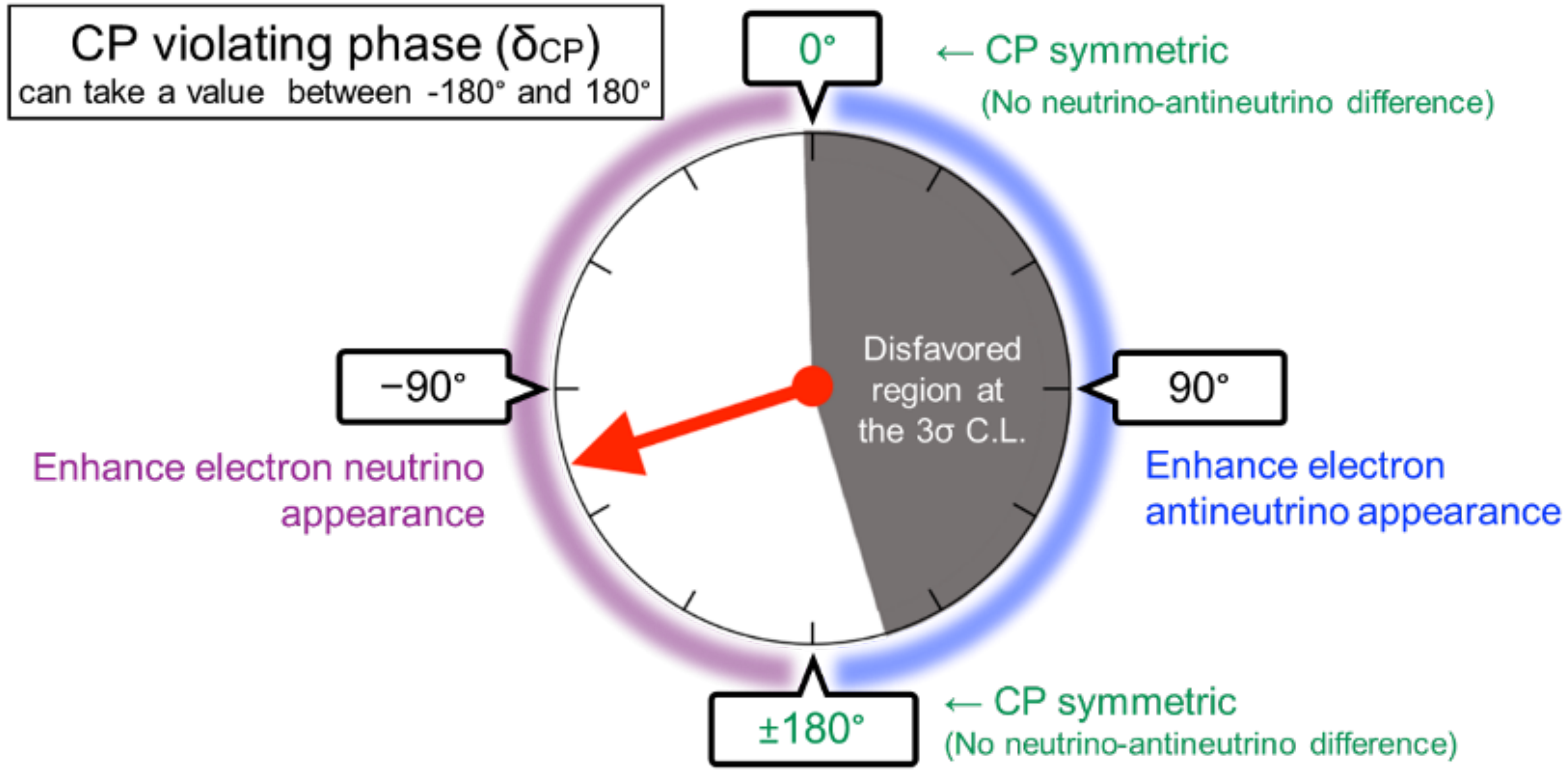
  (Phys. Rev. Lett. 112, 061802 (2014))

- Search for CP violation in the neutrino sector.
  (Nature 580, 339–344 (2020))

- Precise measurement of neutrino oscillation parameters through the ν_μ disappearance studies.
  (Phys. Rev. D 103, L011101 (2021))

- Measurement of neutrino-nucleus interaction cross-sections
  (Phys. Rev. D 101, 112004 (2020))

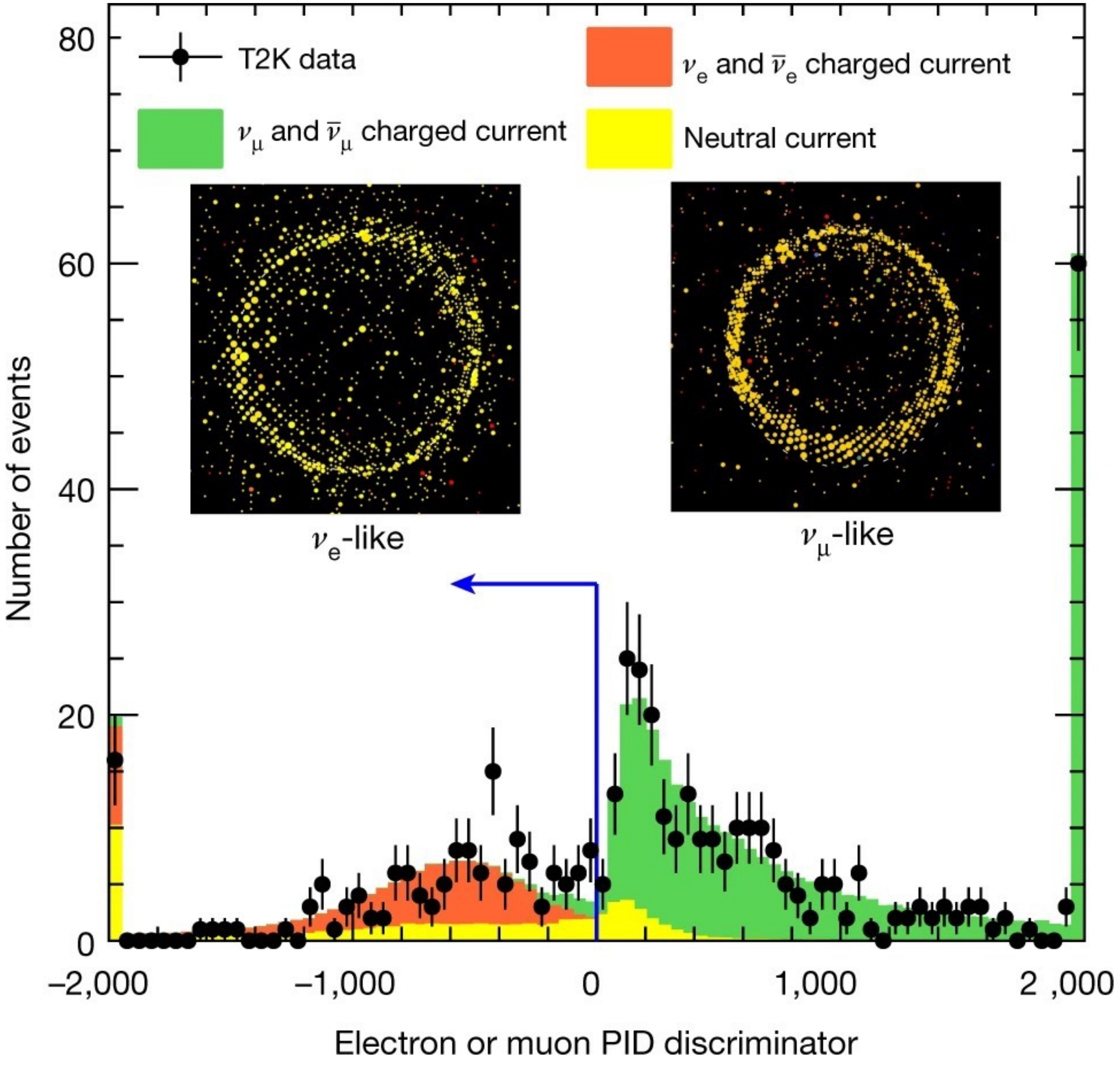
- Probing the sterile components in ν_μ disappearance by studying neutral current (NC) events.
  (Phys. Rev. D 99, 071103(R) (2020))



The grey area shows the range of δ_{CP} values disfavoured at 3σ CL.
Source: t2k-experiment.org

ν_e appearance studies

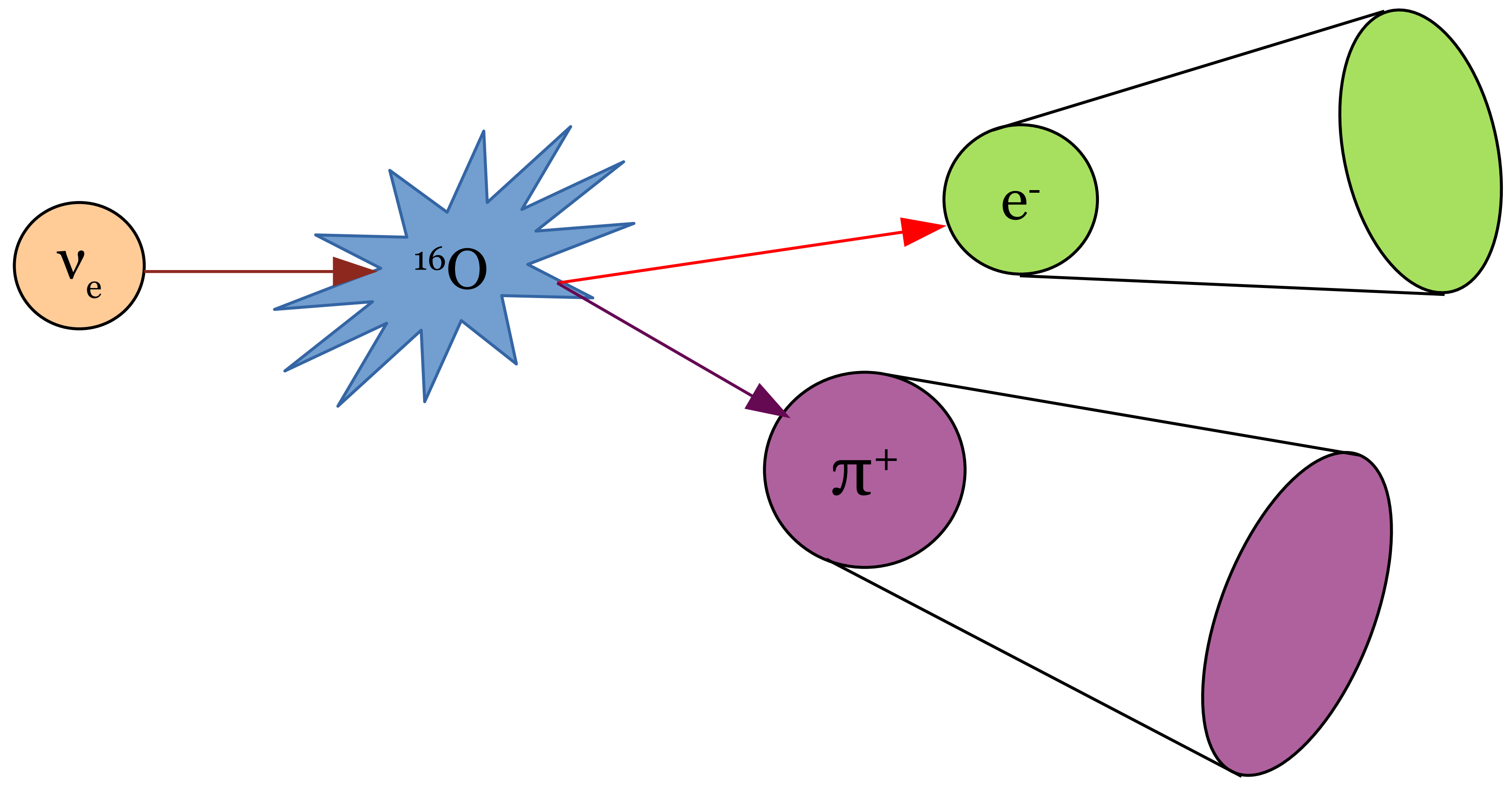
- ν_e that comes from $\nu_\mu \rightarrow \nu_e$ transitions are considered the signal events for ν_e appearance analysis.
- At T2K beam energies, ν_e can interact dominantly via:
  1. $\nu_e + \mathrm{n} \rightarrow e^- + \mathrm{p}$ (1 ring, e-like, CCQE)
  2. $\nu_e + \mathrm{p/n} \rightarrow e^- + \pi^+ + \mathrm{p/n}$ (1 e-like ring + 1 π^+-like ring depending on whether it is above Cherenkov threshold, CCRes)



Source: https://www.nature.com/articles/s41586-020-2177-0

ν_e appearance studies

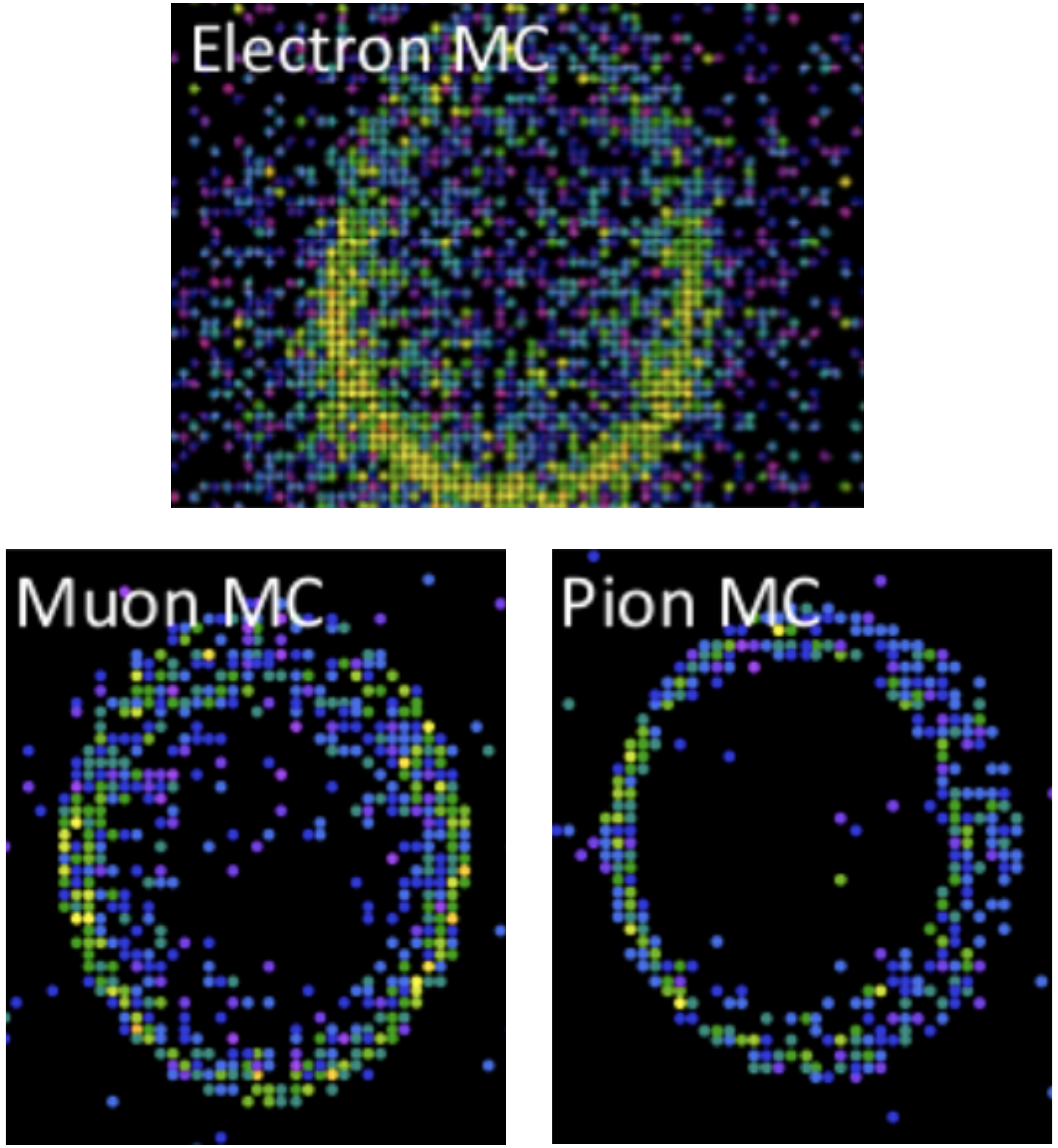
- Currently in T2K analysis, 1-ring CCQE and 1-ring CC1π^+ samples (with π^+ below Cherenkov threshold) are used for the ν_e analysis. This is done by tagging the Michel electrons coming from $\pi^+ \rightarrow \mu^+ \rightarrow e^+$ decay.
- Adding the new 2-ring CC1π^+ sample can improve the statistics of ν_e events at SK and hence improve sensitivity to the CP violation phase δ_{CP}.
- In the anti-neutrino mode, the CC1π^- sample is not used since the π^- will mostly get absorbed by the nucleus before decaying.



2-ring CC1π^+ samples

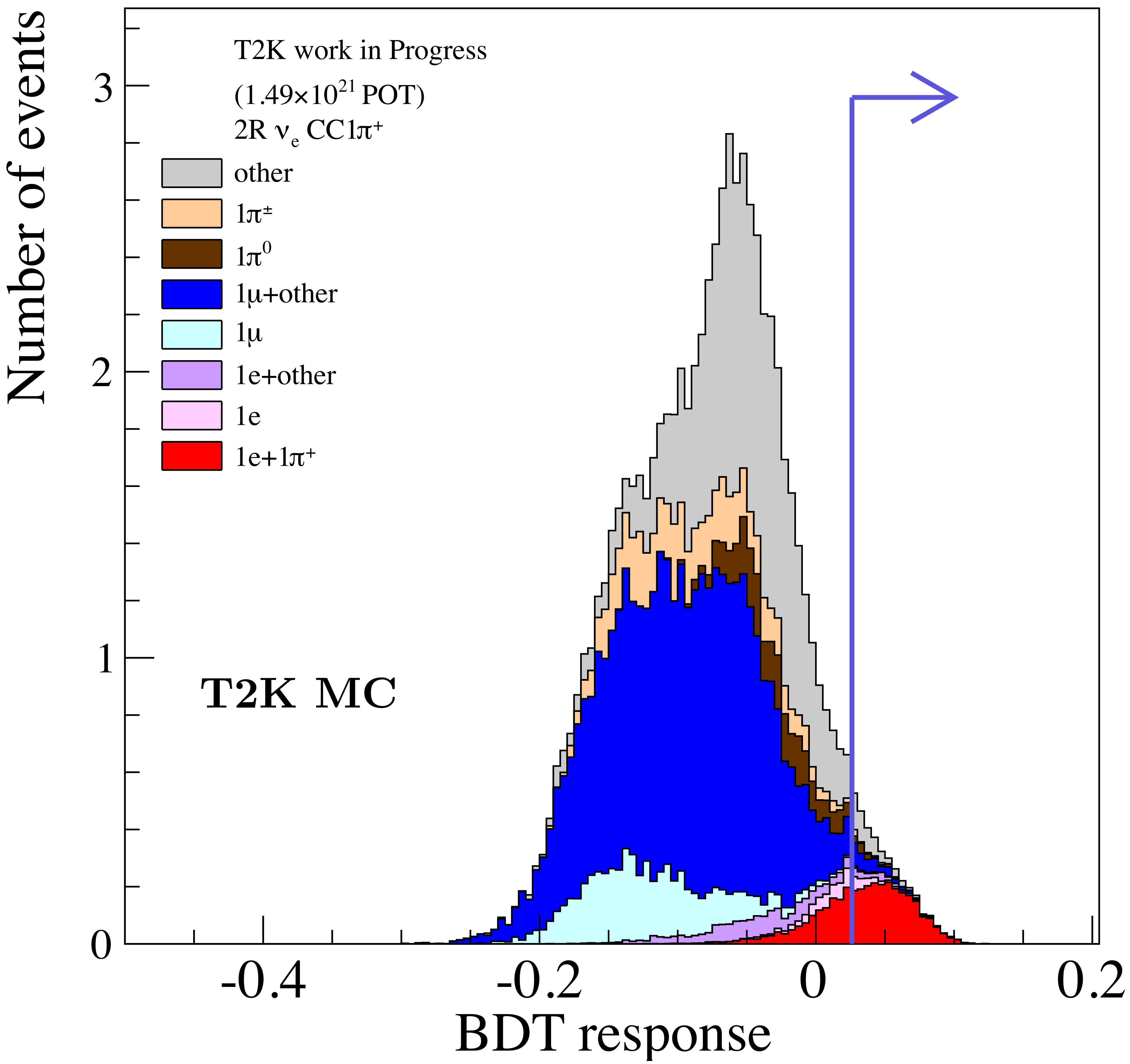
Event reconstruction at SK

- Neutrino events are reconstructed using the fiTQun algorithm that employs a maximum likelihood approach.
- Various particle hypotheses, i.e, whether it is e, μ or π^+ -like are tested using a likelihood function which is generated from charge and time information from SK's PMTs.
- Kinematic parameters such as position, time, direction, momentum and energy loss are reconstructed.
- In the case of multi-ring events, the multi-ring hypothesis is tested by sequentially adding e-like and π^+-like rings.



Selecting 2 ring ν_e CC1π^+ events

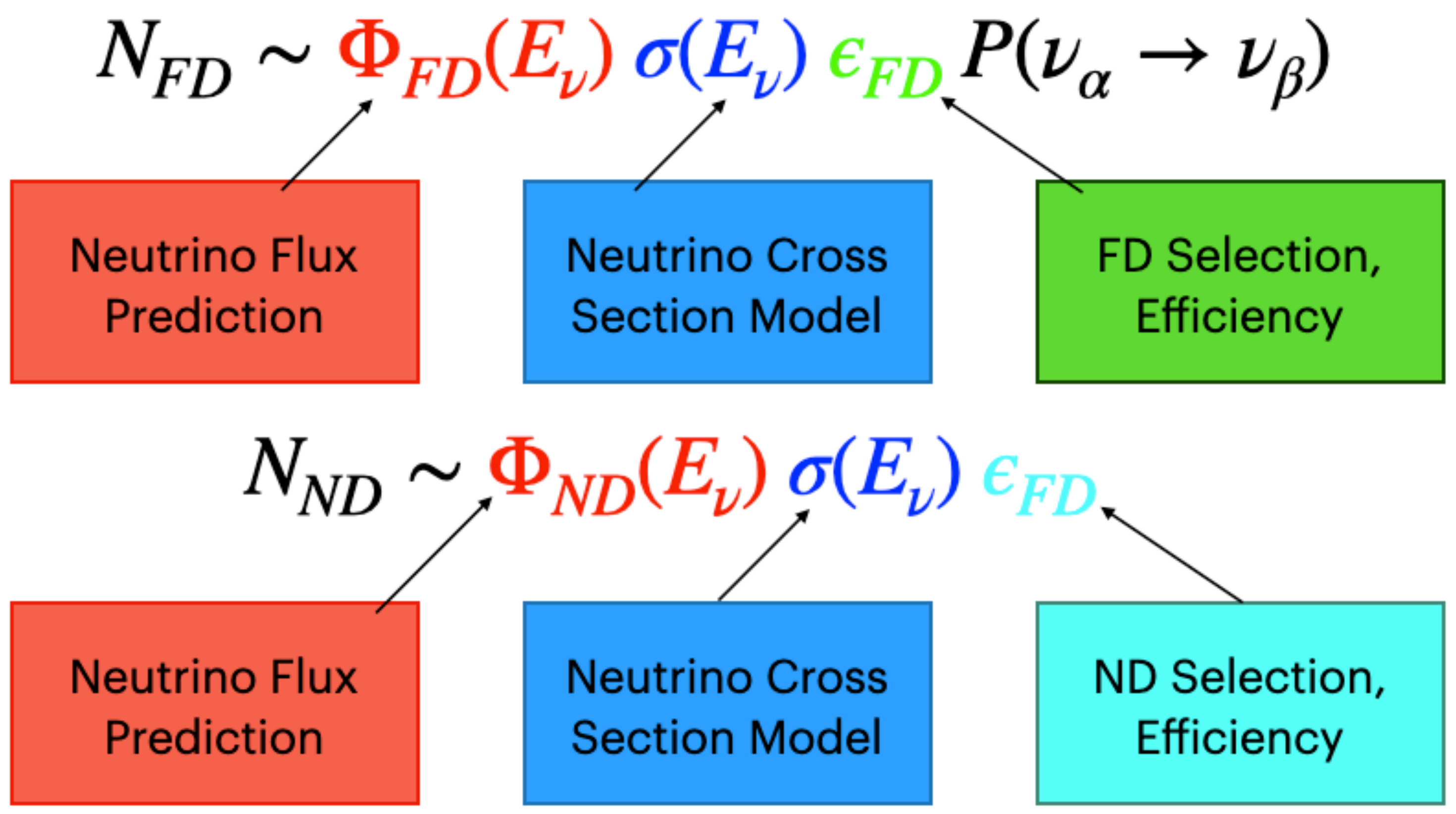
- The currently under-development CC1π^+ selection includes selections based on reconstructed variables and a boosted decision tree (BDT) selection criterion trained on MC simulation of events.
- The pre-selections or the pre-BDT cuts selects those events that are within the fiducial volume of SK, having one decay electron from $\pi^+ \to \mu^+ \to e^+$ decay and with a reconstructed neutrino energy below 1.5 GeV.
- These events then undergo the final BDT selection that makes use of likelihood ratios and reconstructed kinematics from various fits (hypotheses).

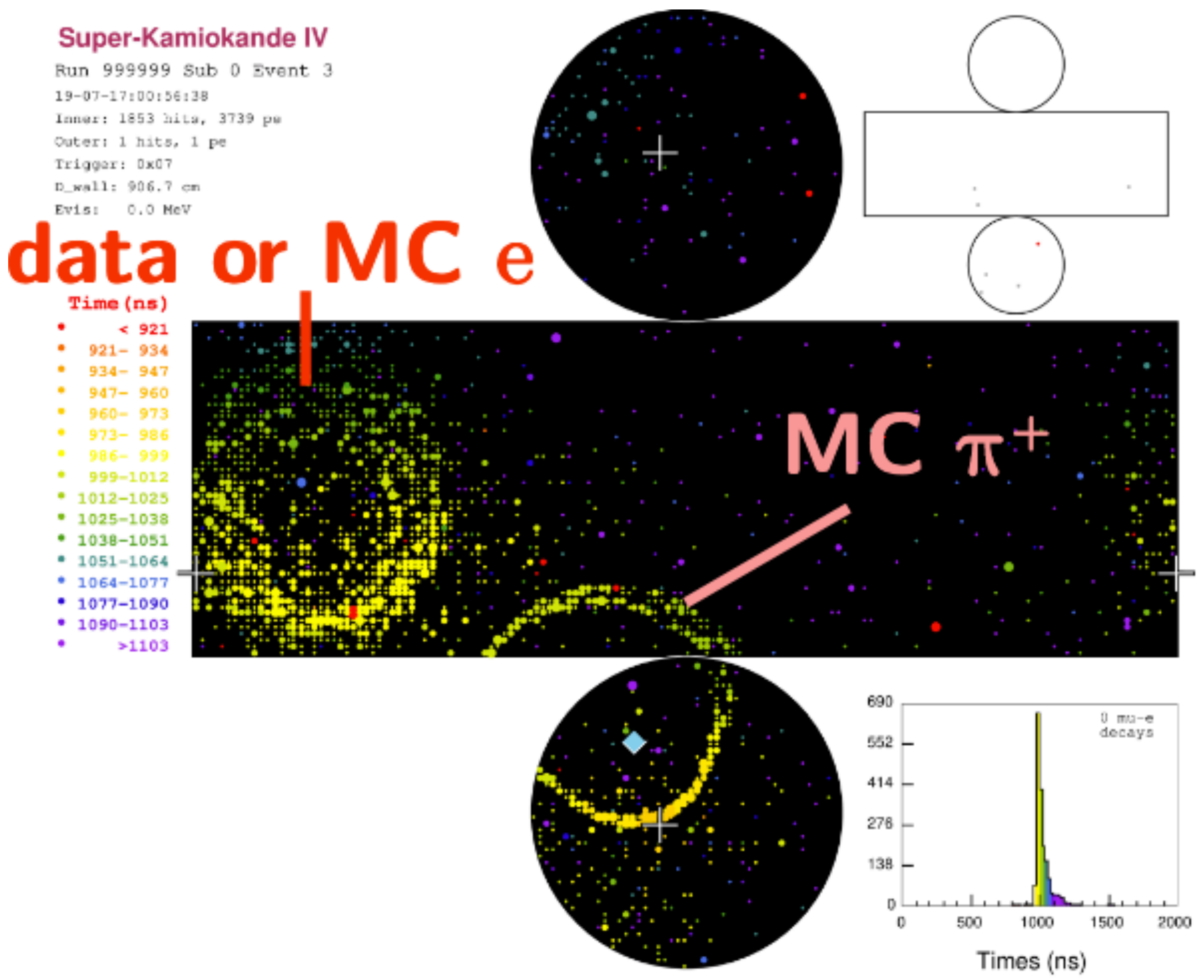


Selecting 2 ring ν_e CC1π^+ events

- When a new sample is introduced in the oscillation analysis, a major step is the determination of systematic uncertainties.
- It can arise from neutrino beam flux, the neutrino interaction modelling, final state interactions (FSI), secondary interactions (SI) and SK detector modelling.
- For example, to constrain the detector systematic uncertainties for the $e\pi^+$-like samples, a comparison is done betweeen two 'hybrid $e\pi^+$samples' generated in the following way:

➡ An MC-generated π^+ is merged with an atmospheric data or MC-generated e using true ν_e CC1π^+ MC kinematics.

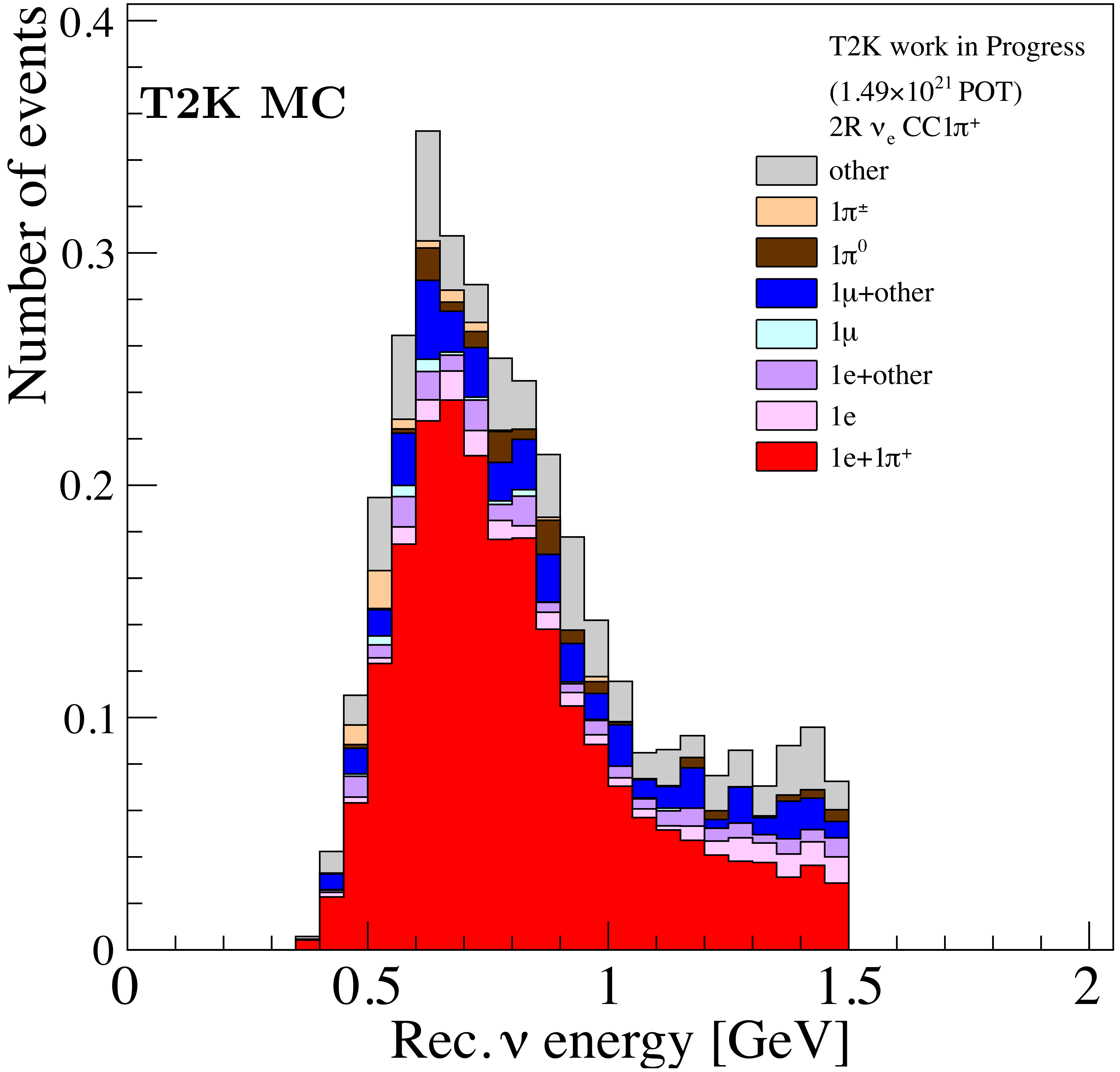




Source: Trevor Towstego. Poster titled "Development of a multi-ring sample at the T2K far detector" at Neutrino 2020

Summary

- A new two-ring ν_e CC1π^+ sample is under development at the T2K far detector which can increase the statistics of the ν_e signal in the ν_e appearance studies.
- Currently, the ν_e CC1π^+ events undergo a BDT based selection.
- My work will be focused on developing a cuts-based selection of ν_e CC1π^+ events.
- This will help in understanding the events better and also a validation of BDT based selections.
- Inclusion of this sample in the T2K oscillation analysis can improve the sensitivity to δ_{CP}.

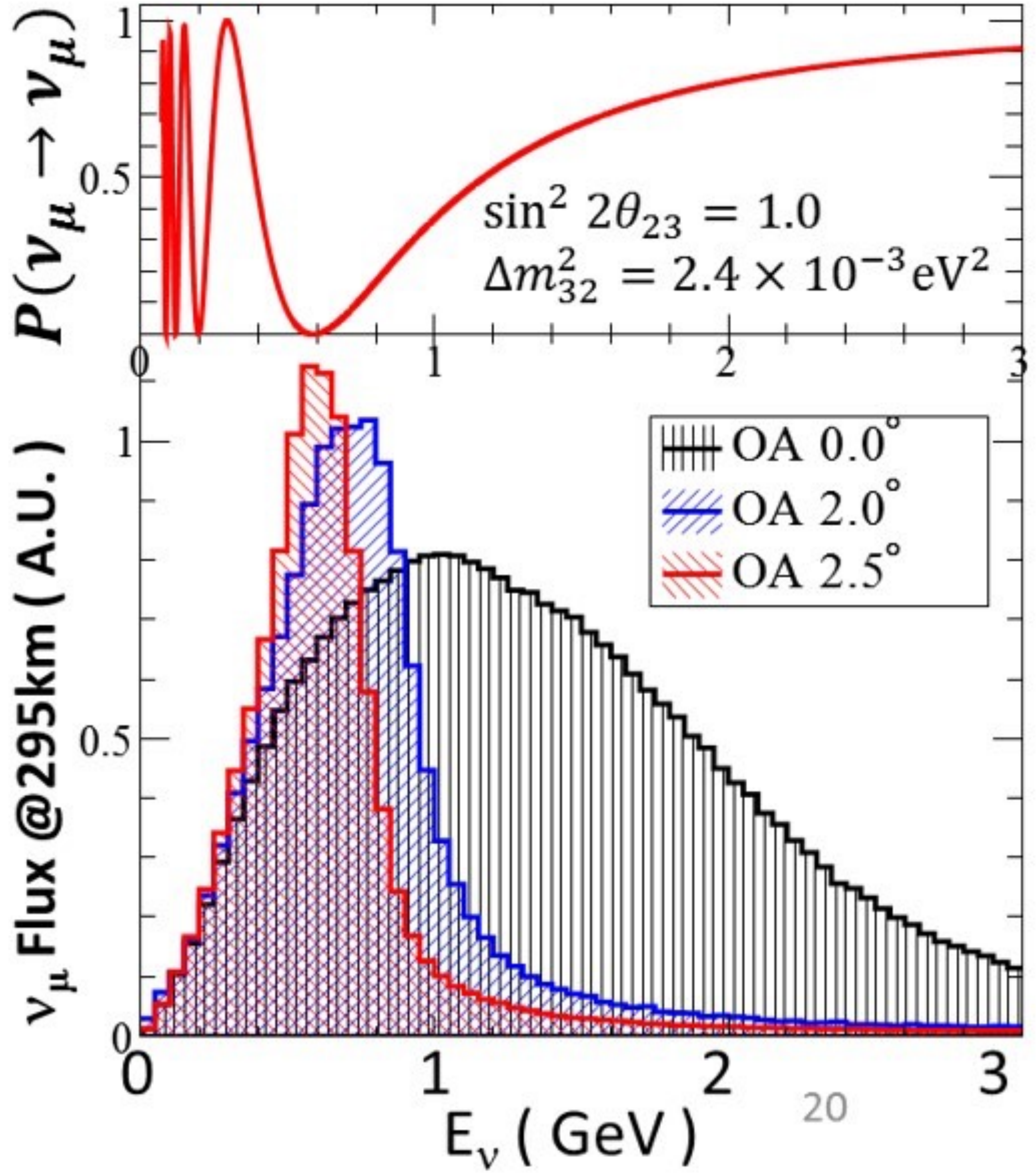


Thank you!

Backup

The off-axis method

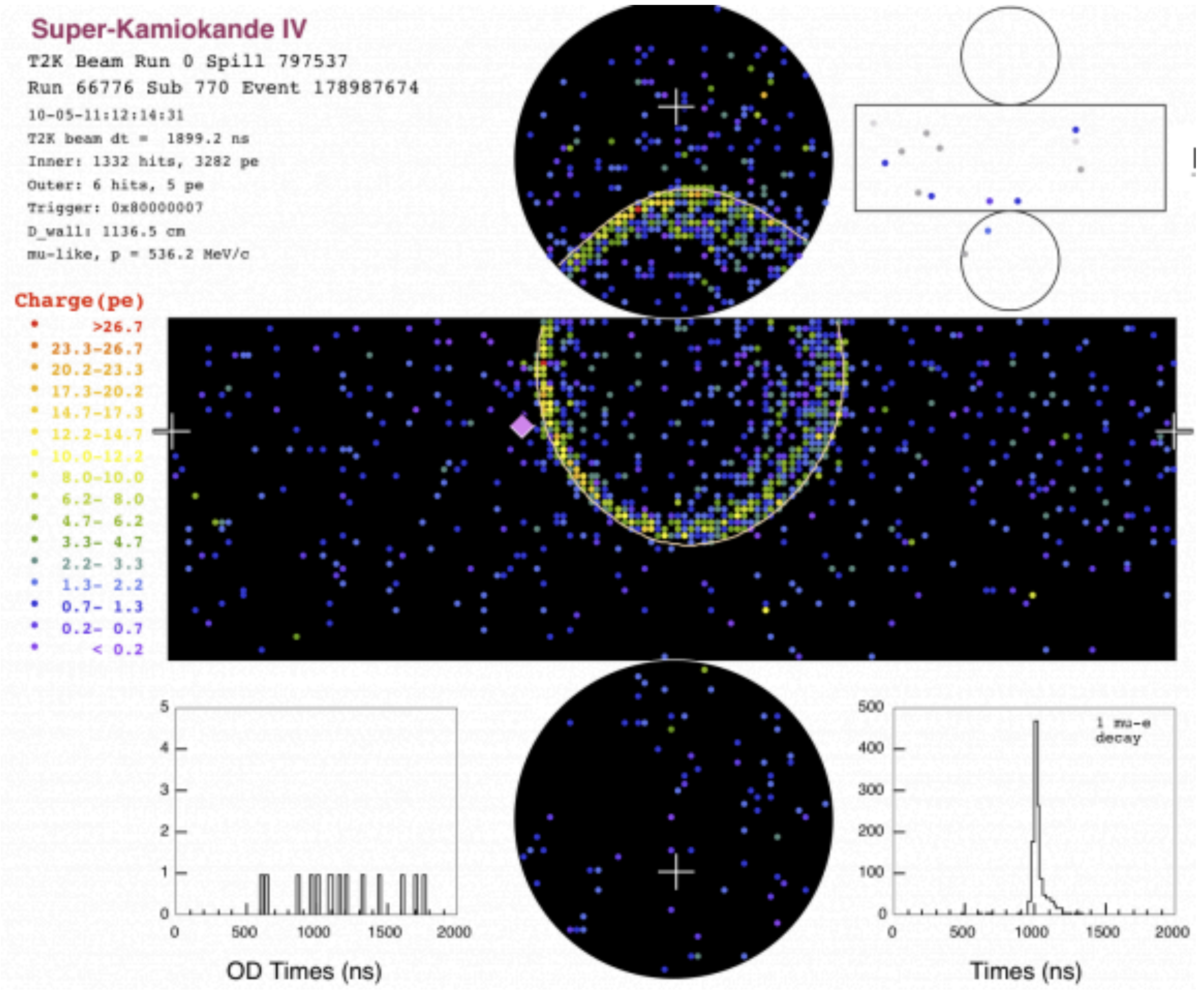
- A disappearance maxima for ν_μ occurs at 0.6 GeV for the baseline of 295km.
- At an off-axis angle of 2.5°, the spectrum of $\nu_\mu(\bar{\nu}_\mu)$ which are produced in charged pion decay peaks at an energy of 0.6 GeV.
- Since most interactions are CCQE at this energy range, the E_ν reconstruction involves a simple 2-body kinematics calculation.
- With the reconstruction of neutrino energy being the most crucial part of the experiment, it is important to work with a narrower spectrum of neutrino energy to get more accurate calculations of oscillation parameters.

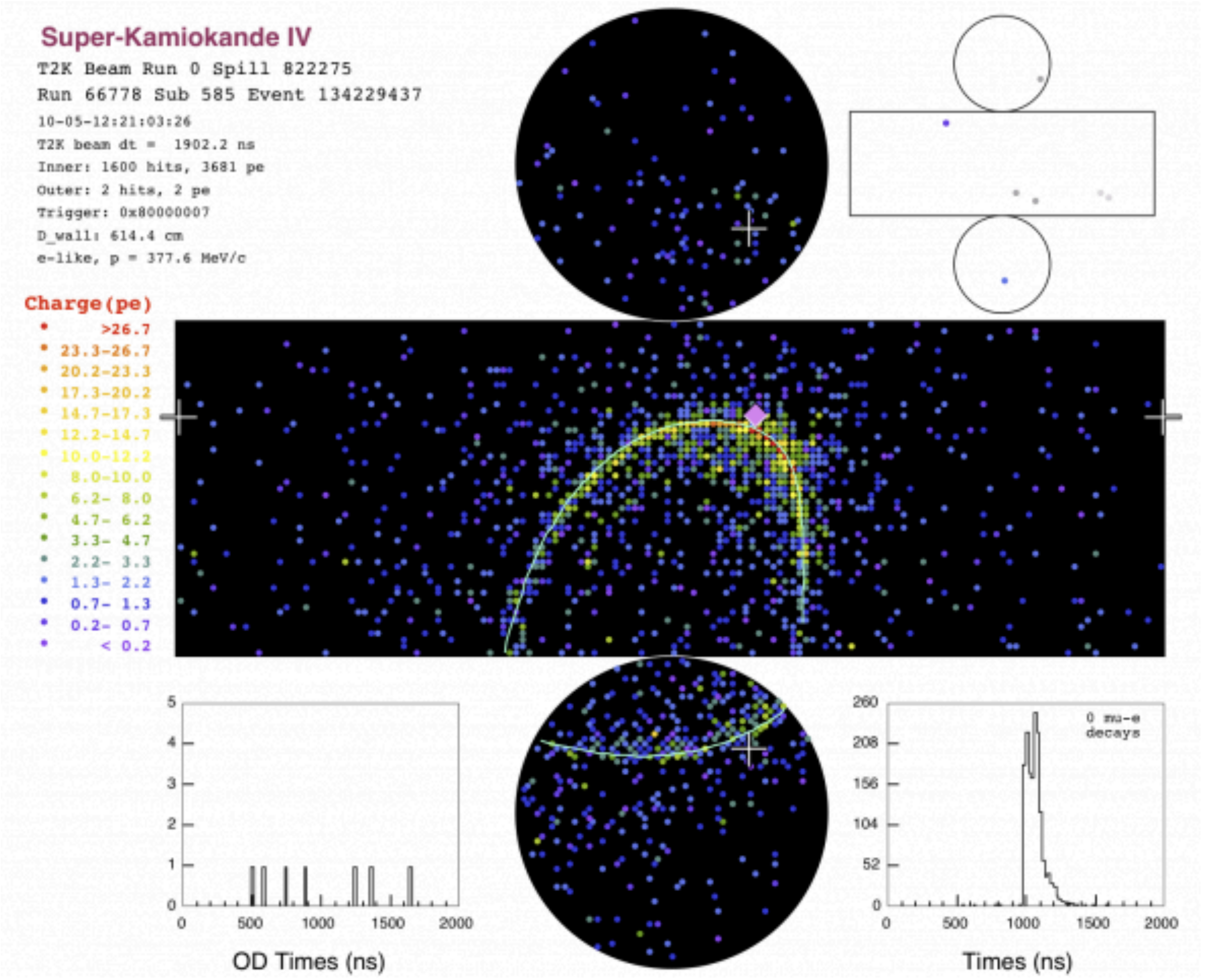


Source: http://www-sk.icrr.u-tokyo.ac.jp/~hayato_s/t2k.html

e/μ ring separation

- The sharpness of the Cherenkov ring is used to distinguish an e-like and a μ-like ring.
- Being a light particle, the electron scatters more frequently than a muon, making the Cherenkov ring appear blurred.
- On the other hand, muons travel almost straight without much scattering making their rings have sharp edges.





Source: https://t2k-experiment.org/photo/super-kamiokande/